Numerische Analyse des Torqueverhaltens von selbstligierenden Brackets im Vergleich zu konventionellen kieferorthopädischen Brackets

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vorgelegt von
Yue Huang
aus
Wenchuan, China

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1. Gutachter: Prof. Dr. rer. nat. Christoph Bourauel
2. Gutachter: Prof. Dr. med. Burger

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Aus der Poliklinik für Zahnärztliche Prothetik, Propädeutik
und Werkstoffwissenschaften der Universität Bonn
Direktor: Prof. Dr. med. dent. H. Stark
- Stiftungsprofessur für Oralmedizinische Technologie -
Prof. Dr. rer. nat. C. Bourauel

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I dedicate this work to my wife Chen-Xin.

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1. Zusammenfassung

In der Kieferorthopädie werden Korrekturen von Zahnfehlstellungen durch kieferorthopädische Bracketsysteme ermöglicht. Ziel dieser theoretischen Arbeit war es, das Torqueverhalten von unterschiedlichen Bracketsystemen miteinander zu vergleichen. Hierbei sollte ein besonderes Augenmerk auf das biomechanische Verhalten sogenannter selbstligierender Brackets gelegt werden.

1.1 Einleitung und Fragestellung

Mit dem Begriff Torque wird in der Kieferorthopädie unter anderem die Winkelfehlstellung der Oberkieferfrontzähne in bukkolingualer Richtung bezeichnet [Rauch, 1959]. Zur Korrektur dieser Fehlstellung werden über Brackets mit Hilfe von unterschiedlich dimensionierten Drähten Torquedrehmomente auf die Zähne übertragen und somit die Bewegung der Zähne im Kieferknochen ausgelöst. Das Drehmoment an sich wird durch die Verwindung (das Torquen oder die Torsion) eines Vierkantdrahtes im Bracketslot erzeugt. In Abhängigkeit von der Größe der Verwindung, der Dimension und der Legierung des Drahtes, dem Spiel des Drahtes im Bracketschlitz sowie der Verformbarkeit des Brackets bewegt der Vierkantdraht durch die im aktivierten Zustand entstehende Torsionsspannung die Zahnwurzel nach vestibulär [Cash et al., 2004; Fischer-Brandis et al., 2000; Harzer et al., 2004]. Weiterhin beeinflusst der Interbracketabstand, somit also die freie Drahtlänge zwischen den Brackets in Abhängigkeit von der Bracketbreite, das erzeugte Torquedrehmoment [Creekmoore, 1976; Hemingway et al., 2001; Schudy und Schudy, 1989]. Die Zusammenhänge zwischen Bracketkonfiguration, Torquedrehmoment, Torquekorrektur und verschiedenen Materialparametern sind äußerst komplex und waren Gegenstand dieser Untersuchung.

Derzeit besteht noch weiterer Klärungsbedarf in Bezug auf die Torquecharakteristik unterschiedlicher Draht/Bracket-Kombinationen. Dies mag insbesondere an der Komplexität der klinischen Situation und an der Vielzahl unterschiedlicher Parameter, die Einfluss auf die Torquecharakteristik haben, liegen [Harradine, 2003]. Die Zahl experimenteller Studien zu diesem Thema ist daher begrenzt, theoretische Untersuchungen, die die klinische Situation realistisch darstellen, sind bislang noch nicht vorgestellt worden.

Seit einigen Jahren werden selbstligierende Brackets durch deren Entwickler und Hersteller mit einer Vielzahl von Vorteilen beworben, so unter anderem mit einem im Vergleich zu konventionellen Brackets verbesserten Torqueverhalten oder mit reduzierten Reibungsverlusten. Als selbstligierend werden solche kieferorthopädischen Brackets bezeichnet, die über spezielle Verschlussmechanismen verfügen, die den Draht im Bracketschlitz verankern. Hierbei ist es nicht mehr notwendig, den Führungsdraht wie bei konventionellen Brackets mit einer Drahtligatur oder einer elastischen Gummiligatur im Bracketschlitz zu sichern.

Selbstligierende Brackets gehen auf Entwicklungen zur Mitte des letzten Jahrhunderts zurück [s. z.B. Cacciafesta et al., 2003; Keim, 2005] und werden derzeit neben dreidimensionalen bildgebenden Verfahren und Miniimplantaten zu einer der zukunftsträchtigsten Entwicklungen in der klinischen Kieferorthopädie gezählt [Keim, 2005]. Jedoch fehlen bislang sowohl fundierte und systematische experimentelle als auch theoretische Studien, die die biomechanischen Eigenschaften dieser Brackets umfassend beschreiben. Durch unterschiedliche experimentelle Ansätze sind die Ergebnisse oftmals widersprüchlich. Die in einigen Studien festgestellten deutlich reduzierten Reibungsverluste bei verbesserten Nivellierungseigenschaften und reduzierten Kräften [Berger, 1990; Berger, 1994; Damon, 1998; Rinchuse und Miles, 2007; Turnball und Birnie, 2007] konnten in anderen Untersuchungen nicht bestätigt werden [Badawi, 2008; Bourauel et al., 2007; Pandis et al., 2007; Pandis et al., 2008; Shivapuja und Berger, 1994].

Für den praktizierenden Kieferorthopäden ist es jedoch außerordentlich wichtig, hinreichend Kenntnis über die Eigenschaften der verschiedenen Materialien und deren Zusammenwirken zu haben, um die Torquekorrektur kontrolliert und bis auf die gewünschte Endkorrektur durchführen zu können. Die hier vorgestellten Untersuchungen zum biomechanischen Verhalten verschiedener Bracketsysteme sollen es dem Praktiker ermöglichen, deren Torqueeigenschaften zu beurteilen und somit eine Hilfestellung zur Auswahl geeigneter Materialien oder Materialkombinationen geben, um schlussendlich eine Erfolg versprechende Behandlung zu ermöglichen.

1.2 Ziele

Ziel der hier vorgelegten Untersuchung war, die Torqueeigenschaften selbstligierender kieferorthopädischer Brackets mit Hilfe der Finite-Elemente-Methode zu untersuchen und mit den Eigenschaften eines ausgesuchten konventionellen Brackets zu vergleichen. Dabei sollte insbeondere geklärt werden, wie neben dem eigentlichen Bracketdesign die Parameter Drahtlegierung, Drahtquerschnitt, freie Drahtlänge sowie Bracketbreite und Ligierungsart das Torqueverhalten beeinflussen.

1.3 Material und Methoden

Es wurden drei unterschiedliche Brackettypen untersucht, darunter auch die Hanson Speed™ (Strite Industries, Cambridge, Ontario, Canada) und Damon® MX-Brackets (Ormco, Glendora, CA, USA), die über spezielle selbstligierende Verschlussmechanismen verfügen. Des Weiteren wurde ein konventionelles Metall-Bracket (Discovery®, Dentaurum KG, Pforzheim) untersucht. Alle Brackettypen stammten aus dem 0,56mm-Slotsystem (0.022 inch).

Zur Untersuchung der biomechanischen Eigenschaften der unerschiedlichen Bracketsysteme wurde die Finite-Elemente-Methode (FEM) verwendet. Die FEM ist ein mathematisch-numerisches Verfahren, bei dem die zu untersuchende Struktur in eine Vielzahl kleiner Elemente zerlegt wird. Die einzelnen Elemente haben dabei die mechanischen Eigenschaften der zugrundeliegenden diskretisierten Materialien. Mit Hilfe der Elastizitätstheorie stellen moderne FEM-Systeme dann halbautomatisch Gleichungssysteme auf, die mit einem Computer gelöst werden können. In dieser Arbeit wurde das kommerzielle FEM-Programmsystem MSC.Marc/Mentat 2005 eingesetzt, das an der Stiftungsprofessur für Oralmedizinische Technologie auf einem Dell-Servercluster betrieben wird.

Für die Simulationen wurde folgendermaßen vorgegangen: Auf der Basis von µCT-Scans (Skyscan 1072HR Aartselear, Belgium) wurden für die Speed- und Damon-Brackets dreidimensionale FE-Modelle erstellt. Dazu wurde die in der Oralmedizinischen Technologie eigens entwickelte Software ADOR-3D [Rahimi et al., 2005] verwendet. Für das Discovery-Bracket standen dreidimensionale CAD-Daten zur Verfügung, die zur Modellgenerierung verwendet wurden. Es wurden jeweils vier Brackets vom linken oberen Schneidezahn bis zum rechten oberen Eckzahn rekonstruiert und mit entsprechenden kieferorthopädischen Drähten verbunden.

Ein Torque von 20° wurde rechnerisch auf den rechten oberen Schneidezahn aufgegeben und das Torquedrehmoment wurde bei Torsion eines Drahtes der Dimension 0,46×0,64 mm² (0.018×0.025 inch) und 0,48×0,64 mm² (0.019×0.025 inch) mit dem FE-

System berechnet. Dabei wurden alle weiteren Brackets fest gehalten. Es kamen drei Drahtlegierungen zum Einsatz: Edelstahl, Titan-Molybdän und Nickel-Titan (NiTi). Bei dem konventionellen Discovery®-Bracket wurden zwei unterschiedliche Ligaturen modelliert: einmal eine elastische und einmal eine Drahtligatur aus Stahl.

Zur Berechnung des Effektes einer unterschiedlichen Bracketbreite auf das Torquevermögen selbstligierender und konventioneller Brackets und zur Bestimmung des Einflusses einer variierenden freien Drahtlänge wurden zusätzliche FE-Modelle generiert: Für die Speed- und Damon-Brackets wurden Modelle entwickelt, die die gleiche Bracketbreite wie das Discovery-Bracket aufwiesen, so dass diese direkt miteinander verglichen werden konnten. Dabei wurde die vollständige Drahtlänge jeweils konstant bei 12 mm für alle fünf Brackettypen gehalten. Für die Discovery-Brackets wurden FE-Modelle generiert, bei denen die Drahtlänge von 12 auf 16 mm in 2 mm-Schritten erhöht wurdesteps. Dabei wurde ausschließlich mit der elastischen Ligatur gerechnet.

1.4 Ergebnisse und Diskussion

Es zeigte sich, dass der Einfluss des Drahtes der dominierende Faktor bei der Erzeugung eines Frontzahntorque ist. Insofern ist eine korrekte Auswahl von Drahtquerschnitt und Drahtmaterial die ideale Vorgehensweise, um ein angepasstes und für die erwünschte Bewegung geeignetes Torquedrehmoment zu erzeugen. Der Einfluss der Ligierungsmethode, ob selbstligierend oder konventionell mittels Elastik oder Stahldraht, war dagegen von geringerem Einfluss. Eine Ausnahme bildete jedoch das ‚aktiv-selbstligierende' Bracket Speed™, das über einen superelastischen NiTi-Verschluss verfügt. Dieses Bracket entwickelte in Verbindung mit dem NiTi-Draht der kleineren Dimension mit 4,0 Nmm die kleinsten maximalen Drehmomente und gleichzeitig das geringste Torquespiel. Dieser Wert lag unterhalb des in der Kieferorthopädie mit 5 Nmm empfohlenen Torquedrehmomentes. Die anderen Brackets entwickelten mit dem NiTi-Draht etwas höhere Drehmomente, die oberhalb des geforderten Wertes lagen (Discovery: 10,6 Nmm, Damon: 9,2 Nmm). Alle weitere Draht/Bracket-Kombinationen erzeugten deutliche höhere Drehmomente von bis zu 75 Nmm (Discovery mit Stahldraht).

Insgesamt konnte festgestellt werden, dass das Bracketdesign und insbesondere die Ligierungsmethode gegenüber den anderen Einflüssen, wie Bracketbreite, freie Draht-

länge, Draht/Slot-Spiel oder Grad der Torque-Fehlstellung einen untergeordneten Einfluss auf Torquekontrolle und Torquedrehmoment hat.
Die vorgelegte Arbeit stellt die Ergebnisse dieser Studie in Form von zwei Manuskripten vor, einer Publikation im „American Journal of Orthodontics and Dentofacial Orthopedics“, die zur Veröffentlichung angenommen ist. Die Arbeit ist in leicht geändertem Format aber in der vom Inhalt her in dieser Form zur Publikation angenommenen Version auf den Seiten 12 bis 28 eingefügt. Diese Publikation behandelt nur einen Teilaspekt der Untersuchungsergebnisse. Daher ist im Weiteren auf den Seiten 29 bis 48 das Manuskript einer zur Veröffentlichung eingereichten Publikation angefügt, in dem ein größerer Teil der Ergebnisse vorgestellt wird. Dieses Manuskript wurde entsprechend der Richtlinien der Zeitschrift „Orthodontics and Craniofacial Research“ verfasst und wird ebenfalls in leicht geänderter Formatierung vorgestellt. Diese Arbeit befindet sich derzeit im Begutachtungsverfahren.

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Numerical modeling of torque capabilities of self-ligating and conventional brackets

Yue Huang[a,b], Ludger Keilig[c], Alireza Rahimi[c], Susanne Reimann[c], Theodore Eliades[d], Andreas Jäger[e], and Christoph Bourauel[f]

Bonn, Germany, Thessaloniki, Greece and Luzhou, China

[a] Luzhou Medical College, China and [b] Doctoral candidate, School of Dentistry, University of Bonn, Germany.
[c] Department of Oral Technology, School of Dentistry, University of Bonn, Germany.
[d] Associate Professor, Department of Orthodontics, School of Dentistry, Aristotle University of Thessaloniki, Greece
[e] Professor and Head of Orthodontics Department, School of Dentistry, University of Bonn, Germany.
[f] CM-Endowed Professor of Oral Technology, School of Dentistry, University of Bonn, Germany.

Running title: Torque moments of self-ligating brackets

Correspondence and reprint requests: Christoph Bourauel, School of Dentistry, University of Bonn, Welschnonnenstr. 17, 53111 Bonn, Germany, E-mail: bourauel@uni-bonn.de

ABSTRACT

Aim The purpose of this study was to investigate the torque capabilities of conventional and self-ligating brackets using the finite element method (FEM).

Material and Methods Three types of brackets were selected: The self-ligating Hanson Speed™ (Strite Industries, Cambridge, Ontario, Canada) and Damon® MX (Ormco, Glendora, CA, USA) as well as the Discovery® (Dentaurum, Pforzheim, Germany) brackets. All brackets were of the 0.022-inch slot size. From the upper left incisor to the upper right canine, four brackets were included in the FE models generated. A torque of 20 degrees was applied to the upper right incisor with 0.46×0.64mm^2 (0.018×0.025-inch) and 0.48×0.64mm^2 (0.019× 0.025-inch) dimension archwires. Three kinds of wire alloys were involved: stainless steel, titanium molybdenum, and nickel titanium. For the conventional Discovery® brackets, two types of ligation were modeled: an elastic and a stainless steel wire ligature. The torque angle/torque moment characteristics in the simulated movement were calculated using the MSC.Marc/Mentat 2005 FE software package.

Results 1) The torque angle/torque moment curves seem to be dominated by the characteristics of the wire. The change of the wire dimension increased the torque moments less than the change of the wire alloy (125% increase for a 0.48×0.64mm^2 instead of a 0.46×0.64mm^2 steel and 220% for a 0.46×0.64mm^2 steel instead of a nickel titanium wire). A combined change of the wire alloy and wire dimension resulted in a 600%-increase for a 0.48×0.64mm^2 steel instead of a 0.46×0.64mm^2 nickel titanium. 2) The play of the 0.46×0.64mm^2 wires was about 9.0 degrees, the play of the 0.48×0.64mm^2 about 7.5 degrees with slightly increased play for the Damon®. 3) The ligation effect of Discovery® brackets with elastic and steel ligatures could be compared to the behavior

of the Damon®. The Speed™ showed different behavior with lowest torquing moments and at the same time smallest torque play.

Conclusions Improving the adaptation of torque movements to the biomechanical reactions of the periodontium is best done by a proper selection of both, wire dimension and wire alloy. The effect of the bracket system is of minor importance, with the exception of brackets with an active clip (with the Speed™ as an example) that displayed smallest play and at the same time lowest torquing moments with all wires.

INTRODUCTION

The interaction between the bracket of an axially rotated tooth and archwire produces a moment. This moment influences the inclination of all teeth in a buccal or lingual direction, particularly the incisors. Torque as described by Rauch[1] is a moment generated by the torsion of a rectangular wire in the bracket slot. The sources of variation in the expression of torque involve: the stiffness of wire alloys, the play between wire and slot, the ligation modes and the bracket design. Recently, the introduction of active and passive self-ligating brackets have presented a challenge to the profession because of the novel ligation mode and the potential alteration in the load and moment expression during mechanotherapy. Whereas some of these systems seem to present reduced friction in vitro, their torquing characteristics are not studied in detail until now.[2-6]

Because of the complexity of the experimental configuration, only little experimental studies have been presented upon torque expression until now, moreover numerical analyses have not been carried out for torque expression in different bracket-archwire combinations.[7-12] The aim of this study was to investigate the torque capability of different bracket and arch wire combinations with respect to varying ligation mechanisms, wire dimensions and wire properties.

MATERIALS AND METHODS

Three types of brackets were selected: The self-ligating Hanson Speed™ (Strite Industries, Cambridge, Ontario, Canada) and Damon® MX brackets (Ormco, Glendora, CA, USA), as well as the conventional ligating Discovery® (Dentaurum, Pforzheim, Germany). All brackets were of the 0.022-inch slot size and made of steel (Young's modulus 200 GPa; Poisson's ratio 0.3). The active clip of the Speed bracket was modeled as being superelastic. From the left upper incisor to the right upper canine, four brackets were included in finite element (FE) models generated either from CAD data of the brackets or from scanning bracket specimens. The canine bracket was included to determine whether there might be differences in the wire deformation on the two different sides adjacent to the right incisor bracket. Figure 1 shows the FE model consisting of the four brackets and the archwire.

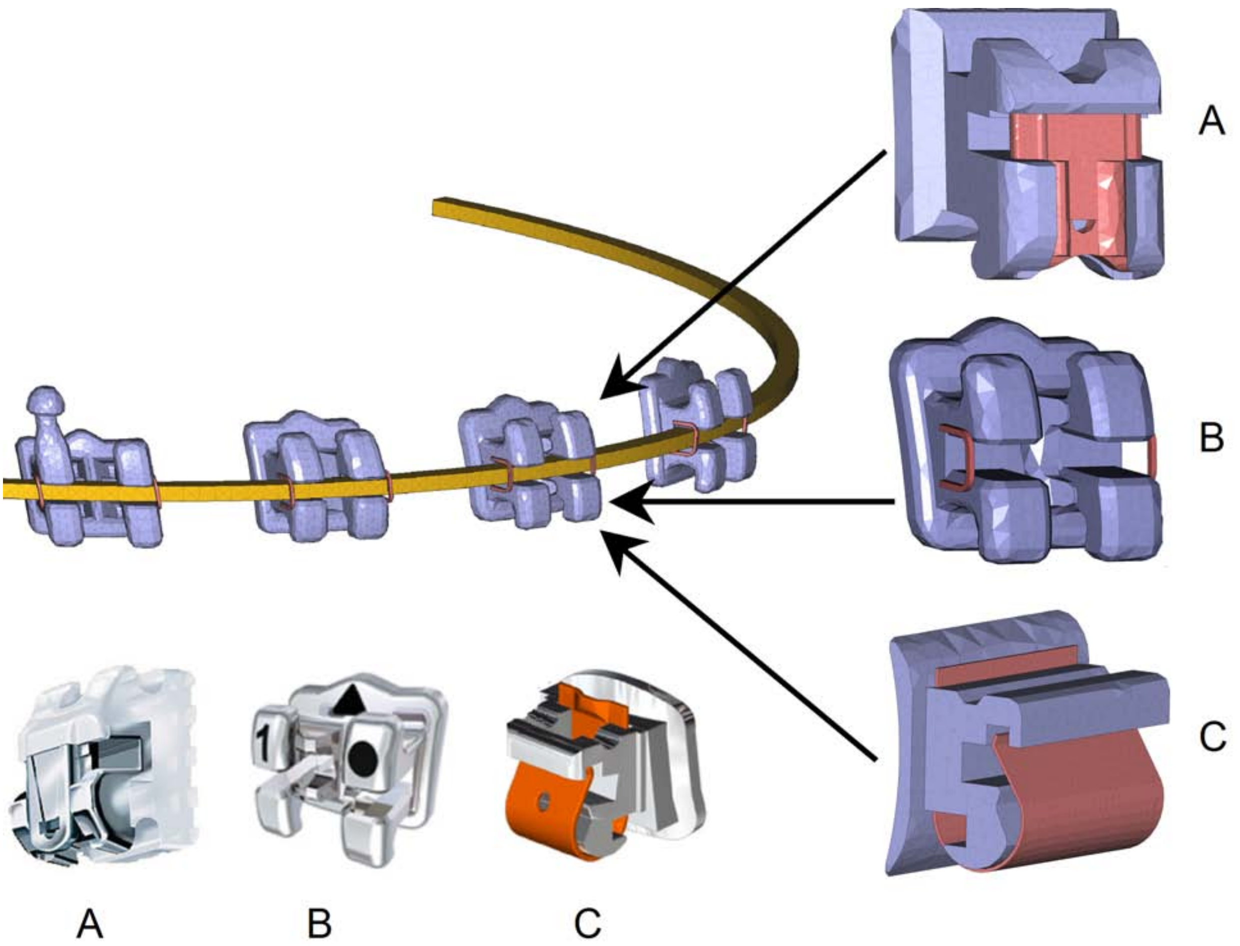

Fig. 1: FE model of the bracket and arch wire combinations. A set of all four brackets of a selected type (A: Damon, B: Discovery, C: Speed) was used in combination with the respective wire. Torque was applied to the right incisor bracket, while the left, the right lateral and the canine bracket remained stationary.

A torque of 20 degrees was applied to the upper right incisor bracket with 0.46×0.64mm² (0.018×0.025-inch) and 0.48×0.64mm² (0.019×0.025-inch) dimension archwires. The total wire length from the left upper incisor bracket to the right lateral incisor bracket was kept constant at 12mm, such that the varying influence of the bracket width on moment generation is taken into account. Further discussion of the free wire length due to variation of bracket widthes will be presented in a forthcoming paper. Three kinds of wire alloys were involved: stainless steel (SS, Young's modulus 200 GPa; Poisson's ratio 0.3), titanium molybdenum (TMA, Young's modulus 80 GPa; Poisson's ratio 0.3), and nickel titanium (NiTi, superelastic behavior; Poisson's ratio, 0.3). All material parameters were taken from manufacturer's references (steel wire, TMA, brackets) or from previous own work (for superelastic behavior). For the conventional Discovery brackets, two ligation methods were modeled: elastic (Young's modulus 0.1 GPa; Poisson's ratio 0.3) and stainless steel wire ligature (Young's modulus 200 GPa; Poisson's ratio 0.3).

Generation of the three dimensional finite element models for the Speed and Damon brackets was done based on cross sectional µCT-scan views of the different bracket specimens (Skyscan 1072HR, Aartselaar, Belgium, resolution: 2µm). The 3D reconstructions were performed with the especially designed software ADOR-3D.[13] The CAD data of the conventional Discovery brackets were provided by the company (Dentaurum).

The following boundary conditions have been applied: A free mobility of the wire within the rotated bracket slot was given. This was realized by performing contact analyses based on the Coulomb friction model. This means that the wire is not deformed until it comes into contact with the slot walls. Thus the wire mobility was restricted by the slot walls and the ligature, respectively. A frictional coefficient µ between the bracket and the wire of 0.2 was used. The bracket of the maxillary central right incisor was rotated from the neutral position by a total of 20 degrees in steps of 0.5 degrees along the central axis of the slot, corresponding to the wire axis. The other three brackets remained fixed in all three planes of space. This means that the wire deformation is influenced by the varying slot width of the brackets.

Simulations of the torque movement were performed with the FE program MSC.Marc/Mentat 2005. As an output, the torque angle/torque moment values in the simulated movement were recorded by the FE software package.

RESULTS

Figure 2 shows selected curves of the simulated torque angle/torque moment characteristics under variation of arch wire dimension, arch wire alloy, and bracket or ligation type. Obviously, the torque angle/torque moment curves seem to be dominated by the characteristics of the wire. Figure 2A and B demonstrate the effect of alloy type and cross section using the Discovery bracket with elastic ligatures as an example. Two characteristic bends can be identified in each curve: The first bend coincides with the play of the wire in the slot of the torqued incisor bracket and has a value of around 9.0 degrees for the smaller wire and 7.5 degrees for the thicker wire. A second bend in the curve (18 and 15 degrees for the small and thick wire, respectively) occurs when the wire comes into contact with the slot walls of the neighboring brackets. These values are similar for all wire alloys. The highest moment (74 Nmm) was generated by the steel wire with the larger cross section, the lowest moment (10 Nmm) by the 0.46×0.64mm2 NiTi.

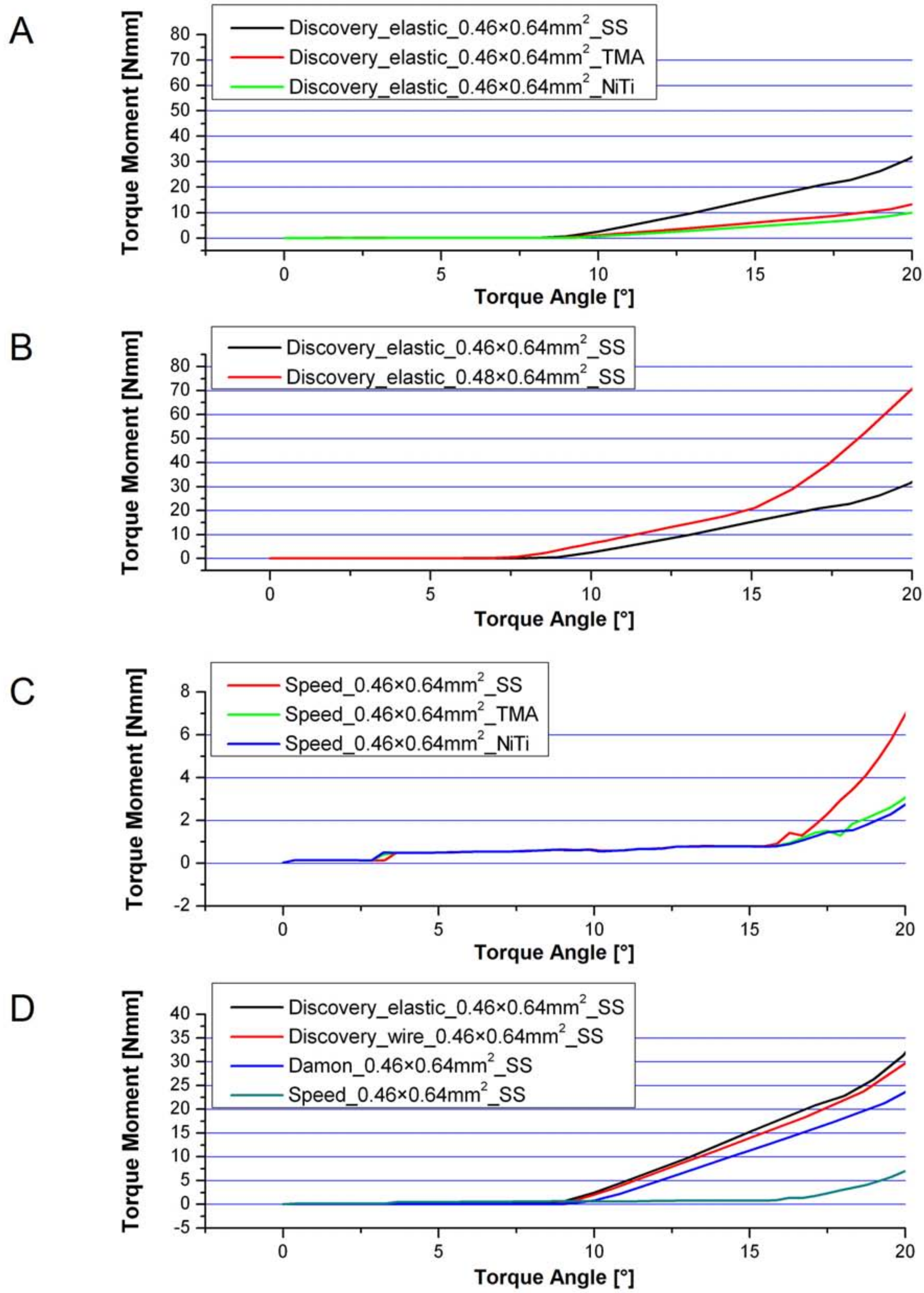

Fig. 2: Moment/torque activation curves of different selected wire bracket combinations. A) Discovery brackets with elastic ligatures under the effect of the arch wire dimension and B) the arch wire alloy. C) Effect of the Speed superelastic active clip. D) Effect of the different ligation methods, investigated with the 0.46×0.64mm^2 SS wire.

Figure 2C shows the special effect of the superelastic Speed clip. The scaling on the moment axis was reduced to a maximum value of 8 Nmm, such that the effect becomes obvious. The Speed bracket displays a minimum play of 2.5 degrees. This is marked by the small step of the curves for all three alloys. Due to the superelastic clip a broad plateau with nearly constant, though very low torquing moment (1 Nmm) for all three alloys ranges from 2.5 to 16.0 degrees. The subsequent bend characterizes the contact of the wire to the slot wall of all brackets involved, the torqued one and the neighboring brackets. The steep increase characterizes the different wire alloys with maximum values of 7.5 Nmm for the SS and 3.0 and 3.5 Nmm for the NiTi and the TMA, respectively.

Figure 2D shows the relationship of the torque angle and the torque moment under the effect of the different ligation methods and engaging a $0.46 \times 0.64 mm^2$ SS wire. The course of the curves of the Discovery with elastic ligature, Discovery with steel ligature and Damon with its rigid, passive clip are similar with a slightly higher play (10.5 degrees) for the wire in the Damon slot. This increased play results in a reduced maximum moment of 25 Nmm compared to the two Discovery values (31 and 34 Nmm). The Speed bracket shows the lowest moment curves within that group.

The bar graphs of Figure 3 show the maximum torquing moments at 20 degrees torque angle for the $0.46 \times 0.64 mm^2$ (A) and $0.48 \times 0.64 mm^2$ archwires (B) with the different bracket types in an overview. The maximum torquing moments, generated by the conventional Discovery bracket with elastic ligature, were about 4.2 times higher than for the Speed brackets. This effect can be attributed to the active clip of the speed. From the other bars the following characteristics that are typical for the engaged wires can be derived: Changing from a $0.46 \times 0.64 mm^2$ NiTi to a TMA with identical cross section increased the torque moment by 34%, and engaging a $0.46 \times 0.64 mm^2$ SS increased the moment by 220%. Increasing the wire cross section to 0.48×0.64mm² increased the moment by 120%. A combined change of the wire alloy and the wire dimension resulted in a 600%-increase for a 0.48×0.64mm² SS instead of a 0.46×0.64mm² NiTi wire. These ratios held for all bracket types.

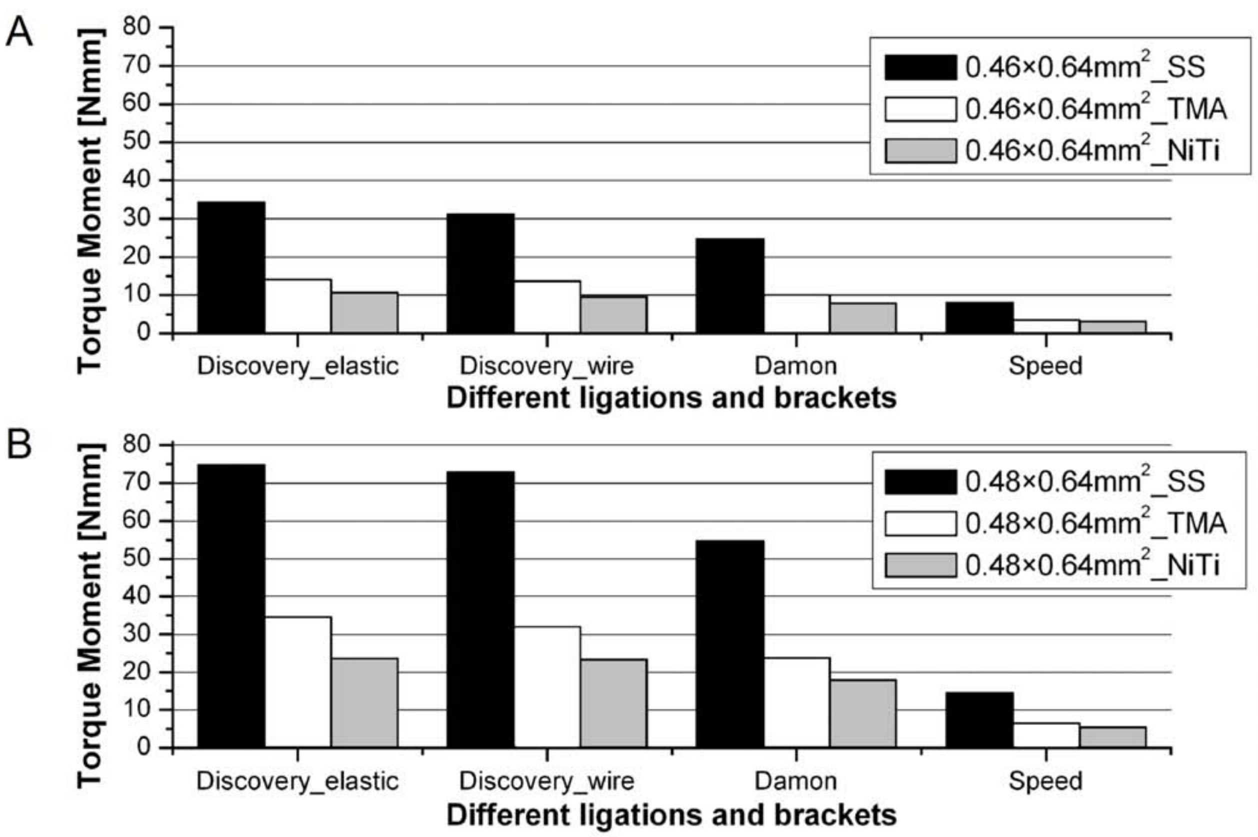

Fig. 3: Maximum torquing moments of the 0.46×0.64mm2 (A) and 0.48×0.64mm2 (B) archwire and bracket combinations.

DISCUSSION

In general, the sources of torque variation consist of manufacturing process effects including milling or casting, varying material properties such as hardness and elastic modulus, and clinical procedures such as the ligation methods and interbracket distance. The influence of variable manufacturing processes was not investigated, and thus not included in this study. Numerical analyses have been performed in order to quantify the effect and compare the influence of varying wire materials and different ligation methods in incisor torque application.

The literature lists effective values for torquing moments in the range of 10 to 20 Nmm[14-16], whereas minimum values of 5 Nmm have been reported for torquing a maxillary central incisor.[17,18] Currently, there is a lack of evidence on the torque characteristics of various bracket/archwire combinations.[19-22] This may be attributed to the complexity of the experimental configuration required in laboratory studies, and the multiplicity of factors needed to be controlled in a clinical setting, including individual response to moments applied, variability in malocclusion and the potential effect of other auxiliaries or treatment utilities in affecting torque.

The results of this numerical study must be analyzed with respect to the clinically relevant factors of torque play and torque moment. The torque angle/torque moment curves of the Speed appliance show the effect of the active NiTi spring during torque control. Up to 16 degrees the three different wire alloys displayed almost similar behavior and obviously there was no play in the curves. This can be attributed to the effect of the NiTi spring, which presses the wire onto the bottom of the slot of the Speed bracket and is activated by the wire upon torquing. However, the torque moment in the initial torquing range was only about 1 Nmm, which according to the above-stated literature is far below the minimum effective moment needed for torquing a tooth. Further torquing of the wire results in its elastic deformation and thus displays the typical characteristics of the different wire alloys. Consequently we can state a real torque play for the Speed bracket of about 16 degrees in case of the 0.46×0.64 mm^2 wires and a reduced torquing moment compared with Damon and Discovery brackets. These two brackets show almost similar activation/torque moment behavior with slightly increased torque play and thus reduced torque moment for the Damon bracket.

When discussing torque play, most studies solely took the play between a single rotated bracket and the wire into account. However, a further factor tends to lower the torque moment of a wire under torsion in a bracket/archwire system, which is the play of the wire within neighboring brackets. The simulated torque moment curves basically show three regions with different slopes in the analyzed bracket/wire systems: Starting with a torque angle of 0 the torque moment remains 0 (or almost 0 for the Speed) until a first bend at an angle of 7 to 10 degrees. This coincides with the torque play of a single bracket/wire system. From that point on the torque rises with a smaller slope until a second bend at 15 to 18 degrees. At this point the wire gets into contact with the slot walls of the neighboring brackets and the torque increases with the torsional stiffness (a higher slope) of the engaged wires. For the Speed bracket the first bend is hardly visible, due to the superelastic behavior of the active clip. However, the behavior succeeding the second bend is similar to the other systems.

Totaling the torque angle/torque moment curves seem to be dominated by the torsional stiffness of the engaged archwires rather than the ligation type. The change of the dimension from 0.46×0.64 mm² to 0.48×0.64 mm² increased the torque moments less than the change of the wire property from nickel titanium to stainless steel, while the change of the dimension from 0.46×0.64 mm² to 0.48×0.64 mm² increased the torque moments more than the change of the wire property from nickel titanium to titanium molybdenum. A further relevant factor influencing the torque behavior more than the way of ligation is the play of the wire in the bracket slots which on the one hand lowers the torque moment but on the other hand reduces treatment efficacy of the bracket system as well. In so far, to make torque movements better fit with the mechanical and biomechanical prevailing conditions, appropriate wire sequences seem to be better means than specialized clip techniques to ligate an archwire in a bracket slot. This of course does not affect any benefits in the clinical procedure using self-ligating compared with conventional brackets.

CONCLUSIONS

The results of this numerical simulation could clearly separate the mechanical effects of various ligating systems from other relevant mechanical quantities, such as wire dimension and alloy, as well as wire/slot play and torque angle. Thus, although FE studies cannot exactly represent the clinical reality, such a study can nicely clarify systematic interdependencies between multiple factors.

The active clip of the Speed bracket reduces torque play but concomitantly lowers the torque moment significantly below the effective moment.

The torque angle/torque moment behavior is determined by the characteristics of the archwire.

Bracket slot/archwire play in the rotated bracket as well as in the neighboring brackets must be taken into account.

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Date: 04/09/2009
To: "Christoph Bourauel" bourauel@uni-bonn.de
From: "American Journal of Orthodontics" ckburke@aol.com
Subject: Your Submission AJODO-D-08-00605R1

Ms. Ref. No.: AJODO-D-08-00605R1
Title: Numerical modeling of torque capabilities of self-ligating and conventional brackets
American Journal of Orthodontics & Dentofacial Orthopedics

Dear Dr. Bourauel,

Thank you for revising your manuscript, "Numerical modeling of torque capabilities of self-ligating and conventional brackets," and resubmitting it to the American Journal of Orthodontics & Dentofacial Orthopedics. You have successfully addressed the reviewers' concerns and I am pleased to accept the paper for publication. It will make a fine contribution to the orthodontic literature.

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Thank you for submitting your work to this journal. I look forward to seeing the article in the AJO-DO.

With kind regards,

David L. Turpin
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Torque capabilities of self-ligating and conventional brackets under the effect of bracket width and free wire length

Y Huang
L Keilig
A Rahimi
S Reimann
C Bourauel

Authors' affiliations:

Yue Huang, Luzhou Medical College, China and Oral Technology, School of Dentistry, University of Bonn, Germany.
Ludger Keilig, Oral Technology, School of Dentistry, University of Bonn, Germany.
Alireza Rahimi, Oral Technology, School of Dentistry, University of Bonn, Germany.
Susanne Reimann, Oral Technology, School of Dentistry, University of Bonn, Germany.
Christoph Bourauel, Endowed Chair of Oral Technology, School of Dentistry, University of Bonn, Germany.

Running title: Torque of conventional and self-ligating brackets

Correspondence to:
Christoph Bourauel
Endowed Chair of Oral Technology
School of Dentistry
University of Bonn
Welschnonnenstr. 17
53111 Bonn, Germany
E-mail: bourauel@uni-bonn.de

Authors: Huang Y, Keilig L, Rahimi A, Reimann S, Bourauel C

Objectives - The purpose of this study was to numerically investigate the torque capacity of conventional and self-ligating brackets under the effect of varying width and free wire length.

Material & Methods - Finite element (FE) models of three kinds of orthodontic brackets in the 0.022-inch slot size were included in the study: Discovery, Damon 3MX and Speed. Additionally FE models of the Speed and Damon brackets were generated with the same width as the Discovery. From the left upper incisor to the right upper canine, four brackets each were included in the study. The total wire length at the upper right incisor was kept constant at 12mm for all brackets types. For the Discovery brackets, the wire length was increased from 12mm to 16mm in 2mm steps. A torque of 20° was applied to the upper right incisor with a $0.46\times0.64mm^2$ (0.018×0.025-inch) and a $0.48\times0.64mm^2$ (0.019×0.025-inch) arch wire. Wires made of stainless steel, TMA, and nickel titanium were studied. The Discovery brackets were ligated with elastic ligatures. The torque angle/torque moment characteristics were recorded.

Results – Wider brackets showed more torque control capability (e.g. Discovery: 10.6Nmm, Damon: 9.2Nmm, Speed: 4.0Nmm for the NiTi wire). Even with the same width as the Discovery bracket, the Damon bracket and the Speed bracket showed lower torque capability, compared with the Discovery bracket. Among them, the Speed bracket which had the same width as the Discovery, generated the lowest torquing moment. Increasing the free wire length decreased the torsional stiffness of the wire, which is the main contributing factor to the torque capability.

Conclusion - The results showed that the bracket design has less influence on the torquing moment than other parameters, such as bracket width, free wire length, wire/slot play, or misalignment.

Keywords: biomechanics, brackets, finite element methods, self-ligation, torque

Introduction

In orthodontics, torque is employed to alter the inclination of all teeth, particularly the incisors. The interaction between the bracket of an axially rotated tooth and arch wire produces a torquing moment. In general, the extent of change in the buccolingual inclination of crowns depends on the wire torque stiffness, the bracket design, the wire/slot play and the mode of ligation (1-3). An additional factor in the clinical routine application of torquing moments relates to the interbracket distance and the bracket width (4-6). The wide array of combinations of the altering factors in defining torquing moments make the empirical clinical determination of the appropriate torquing method a difficult task for the practising professional.

Currently, there is a lack of evidence on the torque characteristics of various bracket/arch wire combinations (3, 7-10). This may be attributed to the complexity of the experimental configuration required in laboratory studies, and the multiplicity of factors needed to be controlled in a clinical setting, including individual response to moments applied, variability in malocclusion and the potential effect of other auxiliaries or treatment utilities, affecting torque.

In the past two decades, there has been a boost in the manufacturing and release of self-ligating appliances with active or passive ligation modes, which attract more and more eyesight because of the time-saving ligation mode and the potential alterations in the load and moment expression during mechanotherapy. Whereas some of these systems seem to present reduced friction in vitro, their torquing characteristics remain uncertain (8).

In a different numerical study it could be demonstrated, that self-ligating Damon and Speed brackets had lower torque capabilities compared to conventional Discovery brackets (11). The torsional stiffness of the arch wire was the significant contributing factor with regard to the torquing moment. However, as the self-ligating brackets were narrower than the Discovery bracket it was difficult to attribute a better torque capability to the Discovery bracket compared with self-ligating brackets. This is due to the fact that the bracket width influences the free wire length and although the torsional stiffness of an arch wire and thus the moment/torque characteristic is dominated by the wire cross section, changing the free wire length is another method to control torque expression.

The presented research aimed at achieving three goals: 1. To analyse the overall bracket effect, i.e. bracket width, wire/slot play, and ligation mode, on the torque capability of conventional and self-ligating brackets. 2. To eliminate the influence of bracket width by rescaling self-ligating brackets to the width of a conventional bracket and thus allowing the analysis of the ligation method effect on the torque capability in the same bracket width. 3. To analyse the torque capability of a conventionally ligating bracket under different free wire lengths by varying the interbracket distance of the upper incisor brackets. The finite element method (FEM) was chosen to achieve the defined goals.

Materials and methods

Three types of bracket systems were selected for this study: the self-ligating Hanson Speed™ (Strite Industries, Cambridge, Ontario, Canada) and Damon™ 3 MX (Ormco, Glendora, CA, USA) brackets, as well as the conventionally ligating bracket Discovery® (Dentaurum, Ispringen, Germany). The widths of the brackets were as follows: Discovery 3.36mm, Speed 2.33mm, and Damon 2.75mm. FE models of the brackets were generated with the respective dimensions. Three-dimensional models of the Speed and Damon brackets were generated on the basis of cross sectional µCT-scan views of the

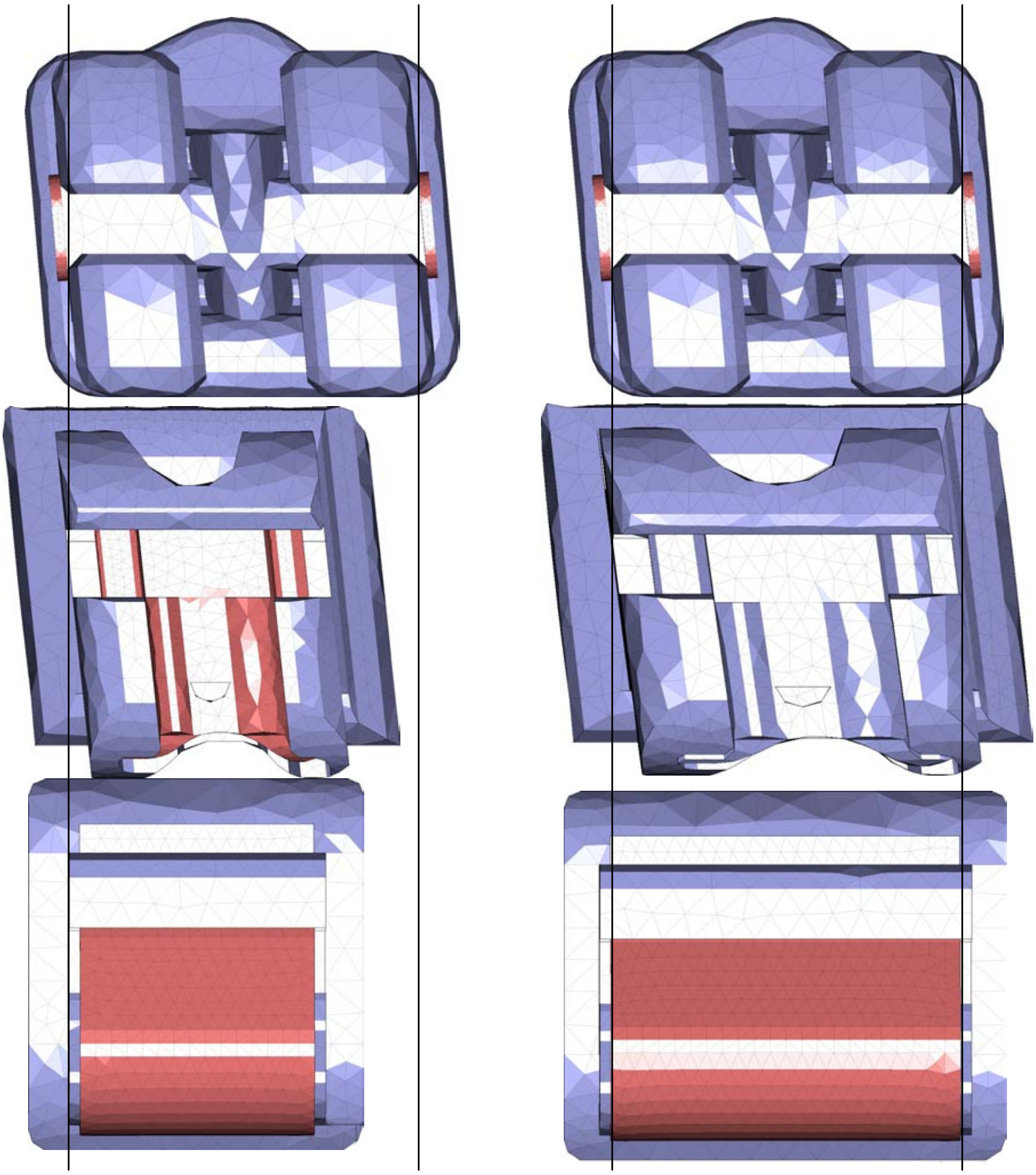

Figure 1: Finite element (FE) models of the brackets investigated: The left column shows the Damon and Speed brackets with original widths compared to the Discovery. In the right column brackets are displayed with the width of the discovery bracket.

different specimens (Skyscan 1072HR Aartselaar, Belgium). The 3D reconstructions were performed using the especially designed software ADOR-3D (12). The CAD data of the conventional Discovery brackets were provided by the manufacturer (Dentaurum, Ispringen, Germany). Additionally two further FE models were generated for the Damon and Speed brackets by rescaling the geometries such that they had the same width as the Discovery bracket. All brackets were of the 0.022-inch slot size. From the left upper incisor to the right upper canine, four brackets were included in the numerical model. Figure 1 shows the FE models of the brackets with varying bracket widths and Figure 2 the full model with four brackets and the engaged arch wire. The following material parameters were assumed for the brackets and ligatures: Discovery – steel (Young's modulus 200 GPa, Poisson's ratio 0.3) with conventional elastic ligature (0.1 GPa, 0.3), Damon - steel (200 GPa, 0.3) with passive steel clip (200 GPa, 0.3), Speed - steel (200 GPa, 0.3) with active nickel titanium clip (superelastic behaviour, 0.3).

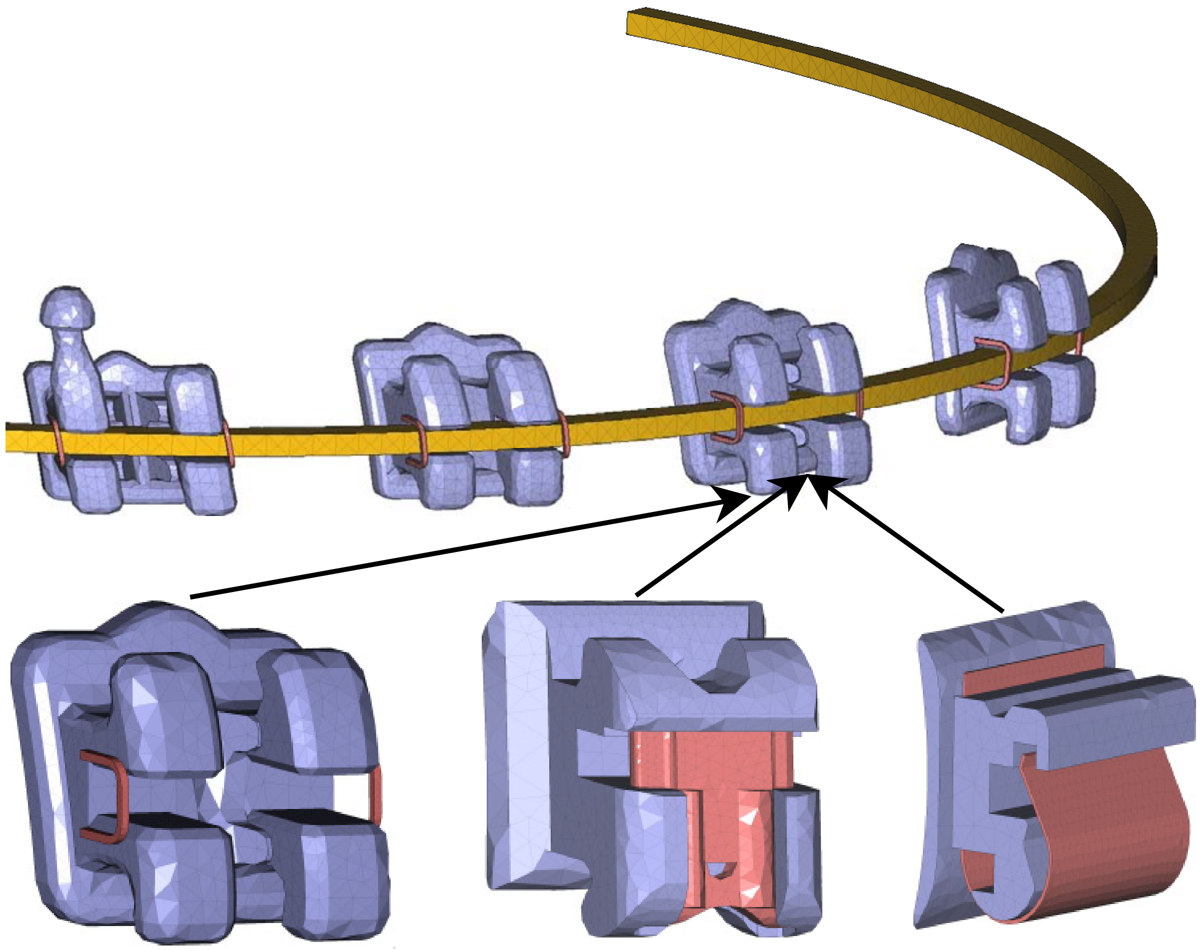

Figure 2: FE model of the overall configuration. Four brackets of each bracket type from the left upper incisor to the right upper canine have been integrated in the FE model.

The total wire length from the left upper incisor bracket to the right lateral incisor bracket was kept constant for all five bracket/wire configurations at 12 mm (see Figure 3) to determine the effect of the bracket type, including ligation mode and bracket width. In order to determine the influence of a varying free wire length the total wire length was increased from 12 mm to 16 mm in steps of 2 mm in the model with the Discovery brackets (Figure 3), i.e. the free wire length was increased from 8.64 mm to 12.64 mm. The following arch wires were used with dimensions of 0.46×0.64 mm^2 and 0.48×0.64 mm^2: stainless steel (short code in figures SS, Young's modulus 200 GPa, Poisson's ratio 0.3), titanium molybdenum (TMA, 80 GPa, 0.3), and nickel titanium (NiTi, superelastic behaviour, 0.3).

The torque capabilities of different bracket/arch wire combinations were determined as follows: A torque of 20 degrees was applied to the upper right incisor by rotating its bracket by 20 degrees in steps of 0.5 degrees along the central axis of the slot, corresponding to the wire axis. All other brackets remained fixed in all three planes of

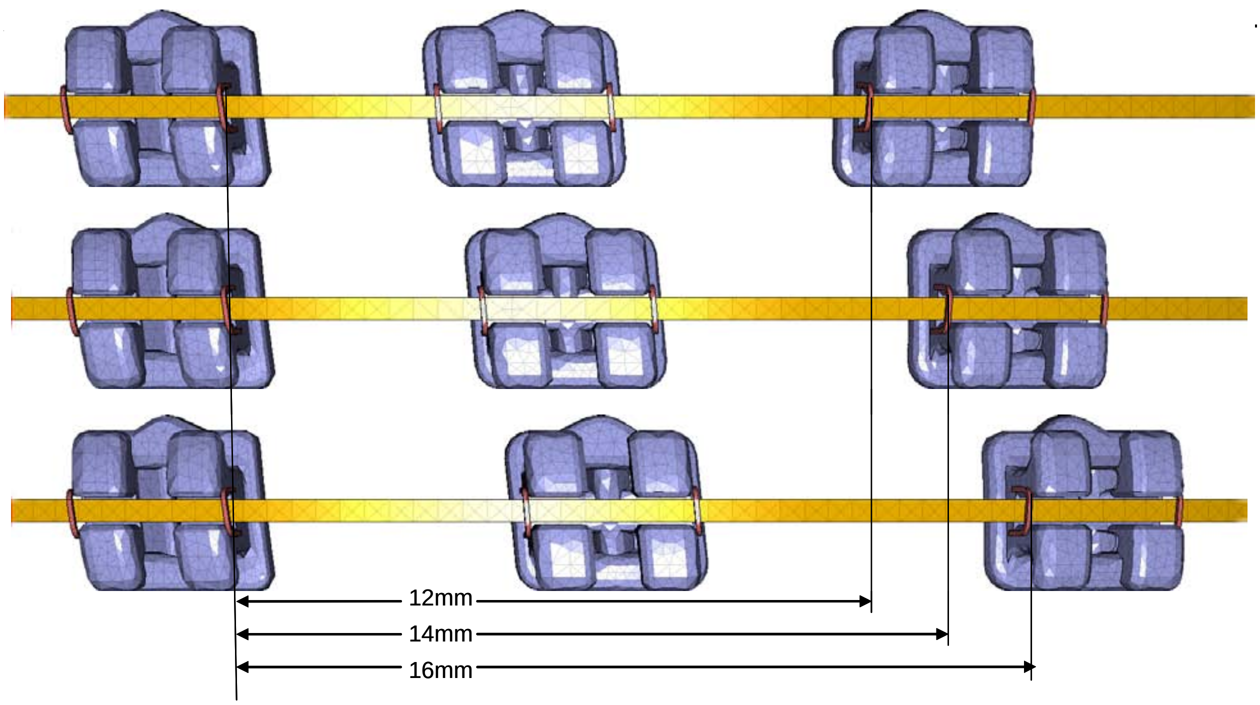

Figure 3: FE model with Discovery brackets and different free wire lengths.

A free mobility of the wire within the bracket slot was given by performing so-called contact analyses with a frictional coefficient μ between the bracket and the wire of 0.2. The wire mobility was thus restricted only by the slot walls and the ligature wire or clip. The torquing moment was generated by a deformation of the wire, comparable to the clinical situation.

Simulations of the torque movement were performed with the FE program system MSC.Marc/Mentat 2005. As an output, torque moment and angle values in the simulated movement were recorded by the FE software package. The torque moment/torque angle curves and maximum torquing moments at 20° torque angle were used to characterise the torquing capabilities of the different bracket/wire combinations.

Results

Figure 4 shows the moment-torque activation curves of the different brackets in combination with the smaller sized wires (0.46x0.64mm²). The following facts can be derived from the graphs: Obviously, all curves have three segments, separated by two bends. The first bend represents the play of the wire in the slot of the torqued bracket of the upper right incisor, up to this point, no moment is generated. For the Discovery bracket this bend can be found at a torque angle of 9.0° (Figure 4a). A second bend is visible when the torqued wire comes into contact with the slot of the neighbouring brackets (18.5°). For all configurations, the fourth bracket in the model did not show an effect on the activation curves, there was no further bending in the curves. The influence of the wire material is clearly visible, the steel wire generates the highest torquing moment and steepest increase, followed by the TMA and the NiTi wires.

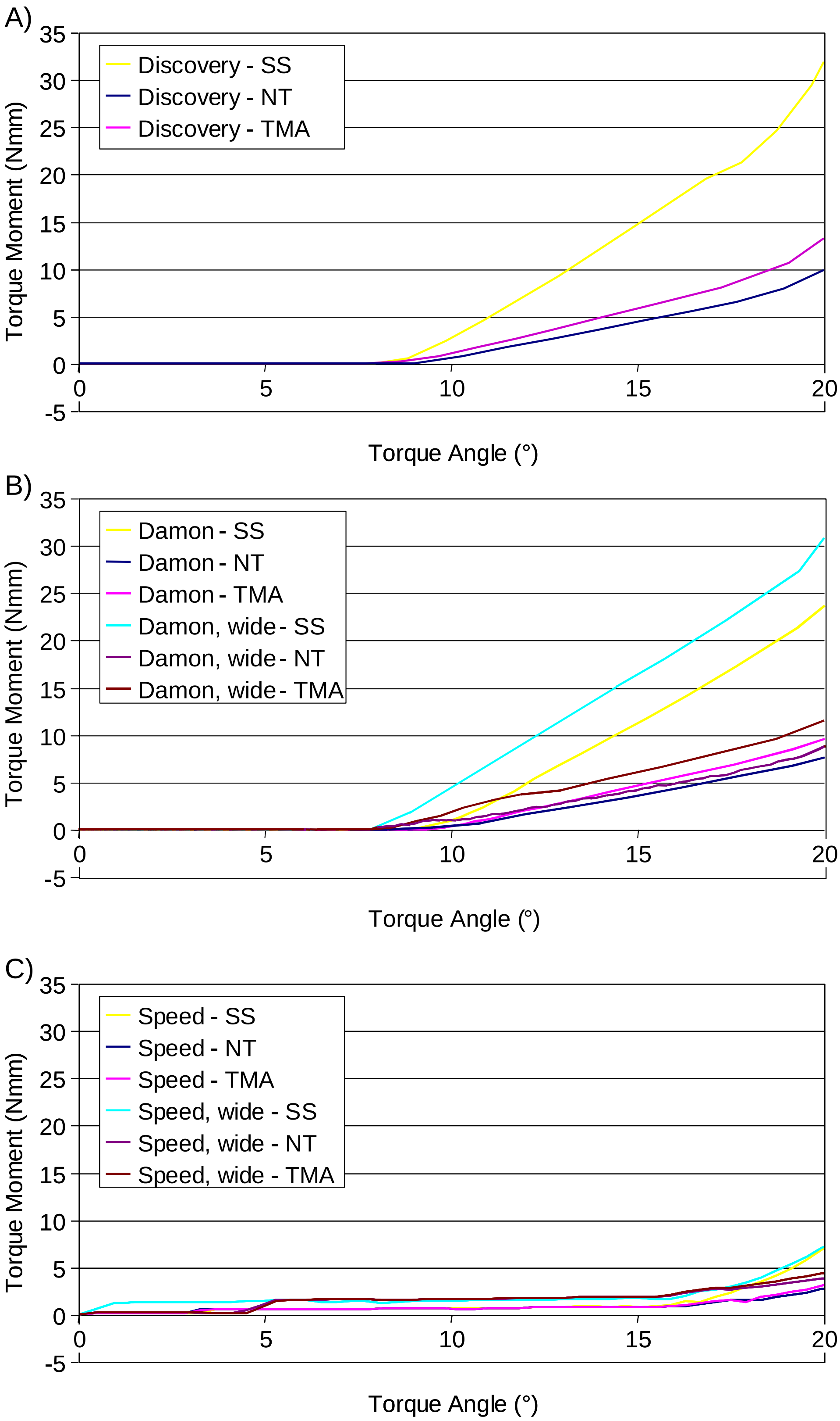

Figure 4: Torque moment/torque angle curves of the bracket types investigated combined with the 0.46x0.64mm² wires (stainless steel: SS, titanium molybdenum: TMA, nickel titanium: NT). (a) Discovery bracket with an elastic ligature, (b) Damon bracket with normal width and with the width of the Discovery bracket (wide), and (c) normal and wide Speed bracket. The effect of the bracket width is obvious.

For the other two brackets we have to distinguish between the activation curves generated by the brackets with commercial width and by the widened brackets. The wide Damon brackets display curves that are quite similar to the curves generated by the Discovery bracket in combination with the respective wire (Figure 4b). Bends can be identified at 8.8° and 18.7°. However, the Damon with the smaller, i.e. conventional width seems to have slightly increased play, as bends in the curves are located at 9.8° and 19.5°. The curve of the Speed bracket (Figure 4c) shows the characteristics of the superelastic NiTi clip. Due to the active clip there is almost no play visible in the curves, however the movement of the clip allows the torqued wire to move within the bracket slot. On the other hand, the moments are extremely small and the bends visible in the curves result from the wires and activated clips that come into contact with the slot walls of the torqued bracket. The play in the neighbouring brackets with the respective bend is not visible and thus the play in the Speed without the active clip would be as high as 16.5°. The order of sequence of the different wires remains unchanged compared with the Discovery bracket.

The maximum torquing moments of the different bracket/wire combinations at a torque angle of 20° is displayed in Figure 5 for the three wire types with the cross sections 0.46x0.64mm² (a) and 0.48x0.64mm² (b). The bar graphs demonstrate quite clearly the effect of the wire type, the wire cross section and the bracket width. The most effective way to alter moments and forces is changing the wire alloy or cross section, while the bracket type is of less importance, except for the Speed. The wire sequence is clearly visible in all bar graphs of Figure 5 (a and b). The highest moment of 75 Nmm is generated by the 0.48x0.64 mm² steel wire in combination with the conventional bracket. The Damon bracket generates roughly 20 per cent lower moments with all respective wires

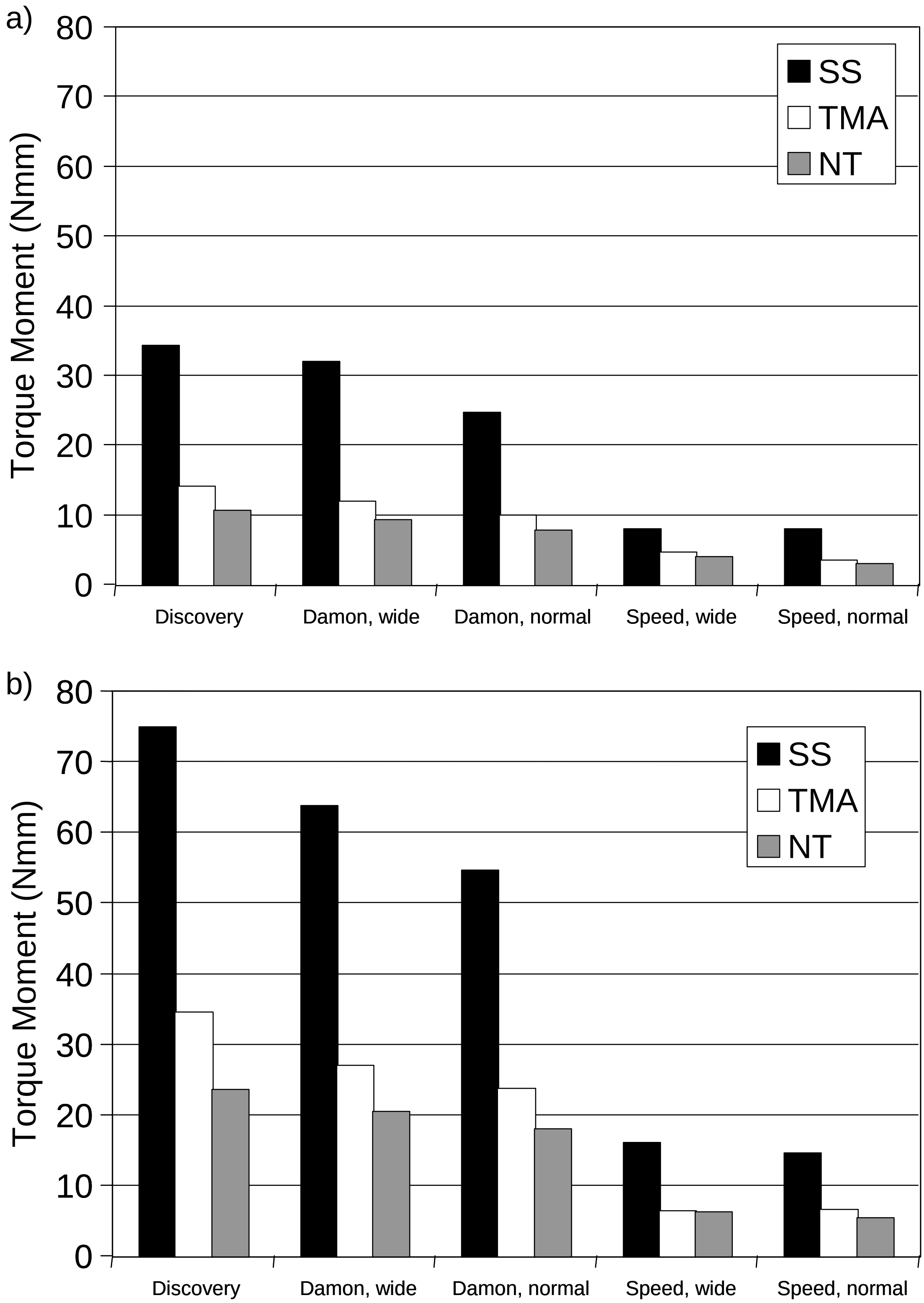

Figure 5: Maximum torquing moment of the different bracket types and the width modifications. (a) Torquing moments at a torque angle of 20° with 0.46x0.64mm² wires. (b) Torquing moments at a torque angle of 20° with 0.48x0.64mm² wires.

and the moments generated by the Speed bracket are only ¼ of the moments generated by the Discovery. The effect of the bracket width is best seen for the Damon bracket in combination with the 0.46x0.64 mm² wires (Figure 5a). The moments for the Damon with the bracket width of the Discovery are increased and almost reach the values generated by the Discovery. The remaining difference may be attributed to the higher play as can be seen in the curves of Figure 4. Figure 6 shows the maximum torquing moment of the different free wire lengths. The increase of the free wire length causes a decrease of the moment of about 15 per cent every 2 mm increase of wire length.

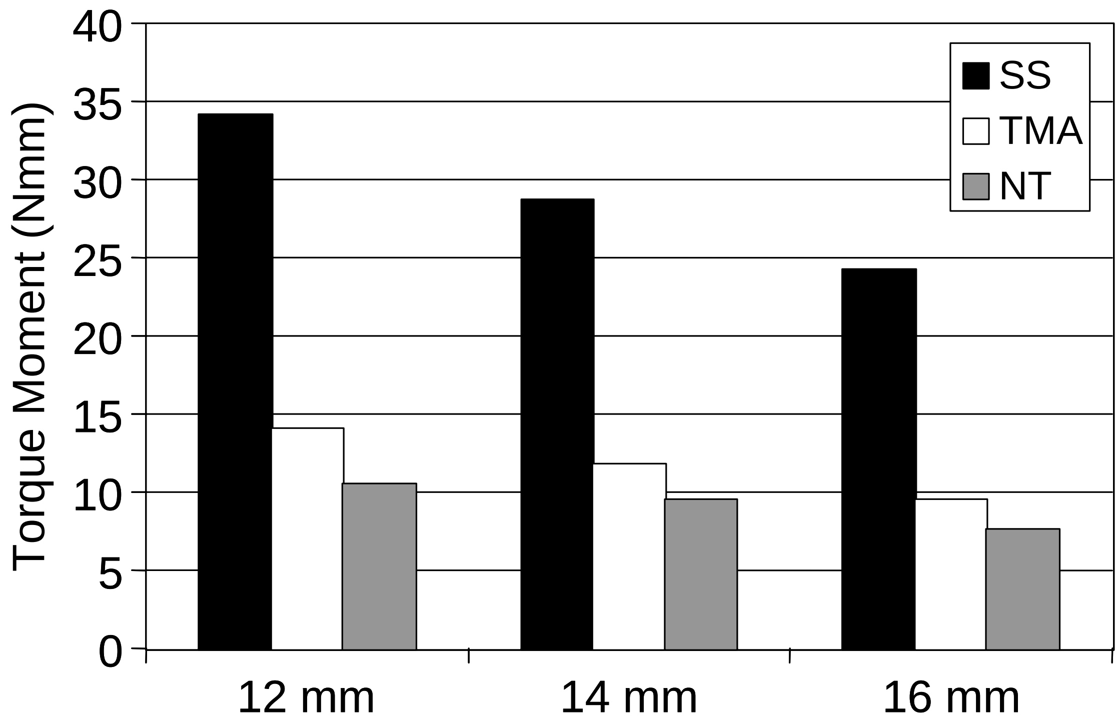

Figure 6: Maximum torquing moment in the FE model with the Discovery bracket and the different free wire lengths.

Discussion

The presented analysis of torque from an ideal arch delivered a couple of practicable guidelines to be used in clinical practice. However, the findings of this study should be viewed in the light of the simplifications and assumptions made. In a former numerical study (11) it was already indicated that ligation methods of the various self-ligating brackets can strongly influence the torquing moment. Compared with a conventional bracket, the self-ligating brackets displayed higher torque play and thus reduced torque capability. However, self-ligating and conventional brackets had different widths, which in turn is a contributing factor to the torque capabilities.

The results of this study show that the self-ligating brackets with increased bracket width increase the torquing moments by about 15% compared with originally sized brackets. Overall, the results show similar moment/torque curves, which seem to be dominated by the characteristics of the wire and the wire/slot play. The wire part that is placed into the bracket slot cannot contribute to the active part of the wire. In essence the bracket is a dead spot that functions like an annealed area (4, 6, 13, 14). Increasing the width of a bracket, on the one hand increases its control capabilities. On the other hand however the torquing moment is increased by the reduced wire length. Clinically, a smaller bracket is more comfortable to the patient, and a compromise must be found between bracket control and generated forces and moments in first and second order bending.

Further discussion of this aspect requires differentiation between Damon (or passive self-ligation in general) and Speed brackets (or active self-ligation). The behaviour of the Damon bracket compared to the conventional bracket can be characterised and explained as follows: The change of the width did not change the shape but the slope of the moment/torque curves (Figure 4), and by this influenced the maximum torquing moments (Figure 5). This effect can be attributed completely to a reduction in the free wire length of the wider Damon. Remaining differences between the standard bracket Discovery and the Damon bracket may be ascribed to different torque play in the systems between the wire, the slot walls and the ligature. In so far, this result confirms that the moment/torque curves are dominated by the torsional stiffness of the arch wires.

The situation is completely changed for the Speed bracket. The activation curves (Figure 4c) clearly show the characteristics of the active NiTi clip. On the one hand there is almost no play, as the clip presses the onto the bottom of the slot and generation of the torquing moment starts with the very beginning of the torque movement. On the other hand however, the generated moments seem to be below or close to the minimum effective values for torquing moments listed in the literature (5 Nmm, see e.g. 15, 16). Only the thicker wires or the steel wire with the smaller cross section generate a sufficiently high maximum torquing moment. The behaviour can easily be explained by the common deformation of the superelastic NiTi clip and the wires engaged into the bracket slot that result in a relatively flat activation curve of the wires compared to the standard or passive self-ligating brackets.

A further contributing factor to torque control is the free wire length (6, 17-19). As Figure 6 shows, stiffness in torsion and thus the generated torquing moment increases as the inter-bracket distance decreases. This result is in agreement with former experimental investigations and with theoretical considerations from basic elasticity theory. Clinically this means that the wider the dental arch, the greater the inter-bracket distance and the lower the moment. Same considerations hold for upper and lower dental arch lengths or for changing from labial to lingual bracket systems. The influence of lingual systems on force systems will be presented in a forthcoming paper.

Further clinical factors influencing torquing moments that could not be studied are the accuracy of vertical bracket positioning or the morphology of the teeth. Several studies proposed different amounts of torque variation. Meyer and Nelson (20) described that a vertical shift of 3 mm can change the torque angle by around 15 degrees, while Miethke (21) proposed that a torque variation of 10 to 15 degrees may already arise from a vertical inaccurate placement of 1mm. The morphology of the teeth can vary greatly and thus affect the clinical use of a torque (22). The angle between the longitudinal axis of the root and the crown at an upper central incisor can also vary (23), modifying the outcome of application of same moment on different shaped crowns. Nevertheless the presented systematic numerical study allows to draw a couple of clinically relevant conclusions.

Conclusions

The results show that the bracket design has less influence on the generated torquing moment than other parameters, such as wire type, bracket width, free wire length, wire/slot play, or degree of misalignment:

- The most important factor with respect to moment generation is the wire type.
- Wider brackets have more torque control ability and generate higher moments.
- Compared with the Discovery bracket, even having the same widths, the Damon brackets showed lower torque capability due to higher play.
- The characteristic of the active Speed bracket in torque is dominated by the NiTi clip. Even with the same width as the Discovery bracket, it generated the lowest torquing moment.
- The increase of the free wire length decreased the torsional stiffness of the arch wire, which in turn is the main contributing factor to the torque capability.
- The larger the free wire length, the less the torquing moment.

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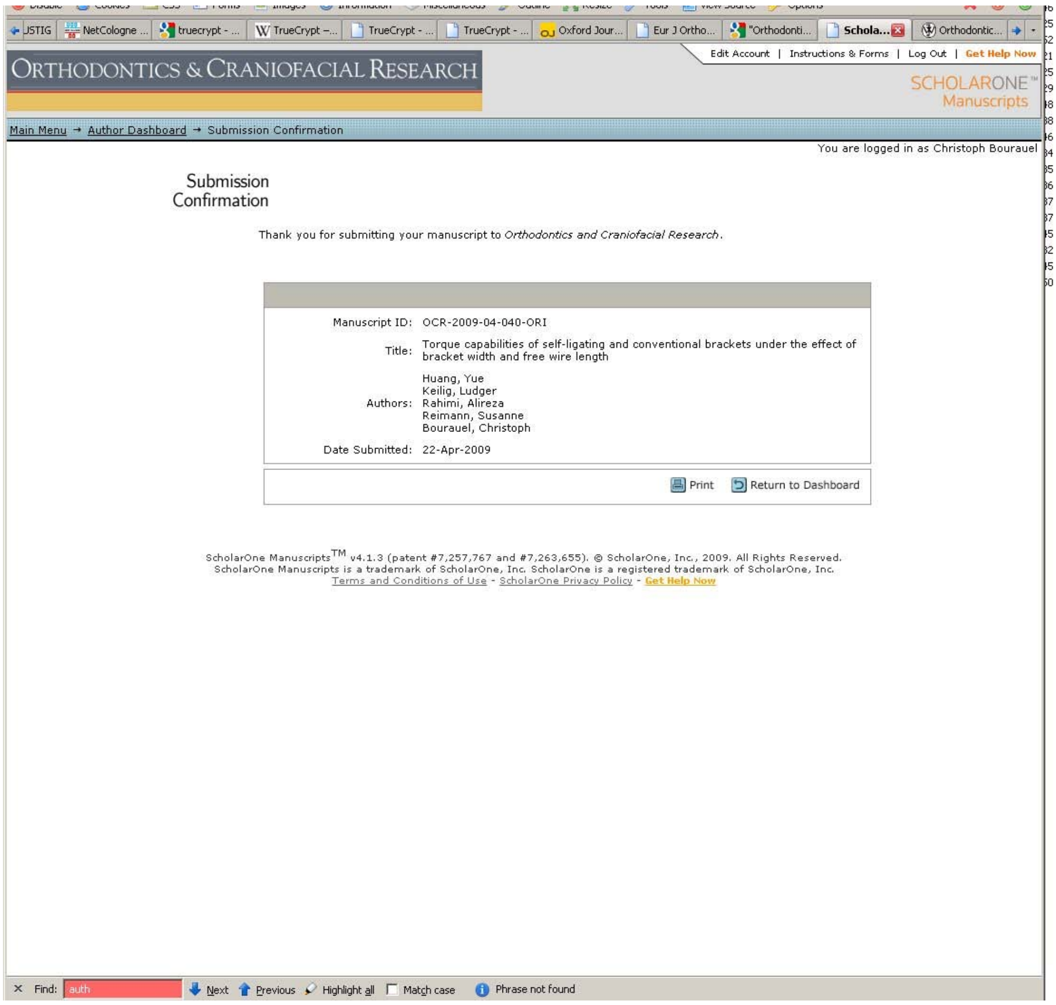

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